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New analysis on narrow baryon resonance decaying into pK_s^0 in pA-interactions at $70\ GeV/c$ with SVD-2 setup.

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Abstract. The inclusive reaction $pA \to pK_s^0 + X$ was studied at IHEP accelerator with 70 GeV/c proton beam using SVD-2 detector. Two different samples of K_s^0, statistically independent and belonging to different phase space regions, were used in the analyses and a narrow baryon resonance with the mass $M = 1523 \pm 2(stat.) \pm 3(syst.)\ MeV/c^2$ was observed in both samples of the data. The combined statistical significance was estimated to be of 8.0 (392 signal over 1990 background events). Using the part of events reconstructed with better accuracy the width of resonance was constrained to $\Gamma < 14\ MeV/c^2$ at 95% C.L. The x_F distribution was found to have a peak at zero with $< |x_F| > \approx 0.1$, that qualitatively agrees to a Regge-based model predictions. A new cross section estimate of $\sigma \cdot BR(\Theta^+ \to pK^0) = 4.9 \pm 1.0(stat.) \pm 1.5(syst.)\ \mu b/nucleon$ for $x_F > 0$ was obtained.

1 Introduction.

In the last years the observation of a narrow baryon state named Θ^+ predicted by Diakonov, Petrov and Polyakov[1] has been reported by a large number of experiments in the nK^+ or pK_s^0 decay channels [2,3,4,5,6,7,8,9,10,11]. However, several experiments, mostly at high energies, did not confirm the existence of Θ^+. The complete list of references to positive and negative results with discussion can be found in [12,13,14]. The situation became more intriguing when CLAS collaboration reported negative results on Θ^+ photoproduction off proton and deutron with high statistics[15]. Meanwhile LEPS collaboration reported on another evidence of Θ^+-baryon in the reaction $\gamma d \to \Theta^+ \Lambda^*(1520)$[16]. The STAR collaboration observed the double charged exotic baryon in the pK^+ decay channel[17]. Therefore, pentaquark existence is still under the question and new experiments are needed to confirm or refute it.

The SVD-2 collaboration has reported earlier the observation of narrow baryon resonance in the pK_s^0-system with the mass of $M = 1526 \pm 3(stat.) \pm 3(syst.)\ MeV/c^2$ and $\Gamma < 24\ MeV/c^2$[9]. In that analysis the K_s^0-mesons decayed inside vertex detector were used (decay region $2 - 35$ mm, zero stands for the center of the 1st target plane). In this paper we present our new results of the study of the same reaction:
$pN \to \Theta^+ + X,\ \ \Theta^+ \to pK_s^0,\ \ K_s^0 \to \pi^+\pi^-$.
We have used two independent data samples, selected by the point of K_s^0 decay: inside and outside the vertex detector (decay regions $0.2 - 35$ and $35 - 600$ mm, respectively). First results of this work were published earlier ([18,19]).

2 SVD-2 experimental setup.

A detailed description of SVD-2 detector and the trigger system can be found elsewhere[9,20,21]. For these studies, we used the following setup components (Fig.1):

1. the high-precision microstrip vertex detector (MSVD) with five active (Si) and two passive (C,Pb) target planes (AT);
2. large aperture magnetic spectrometer (LAMS) : multiwire proportional chambers (MWPC) with Y(vertical), U($Y - 10.5°$) and V($Y + 10.5°$) wire directions;

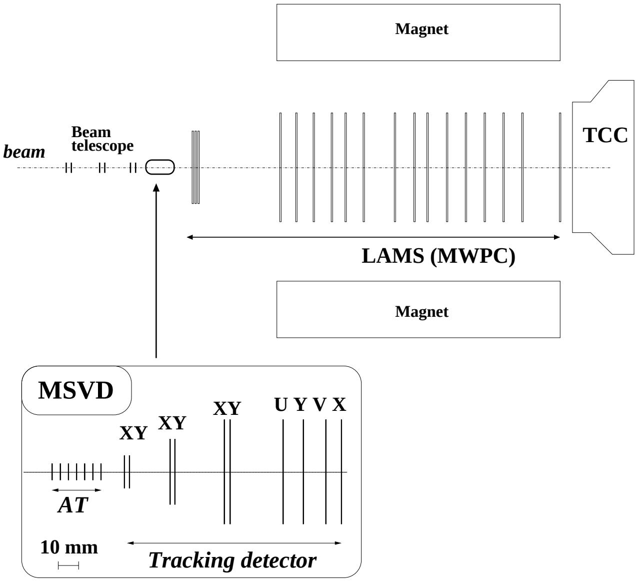

Fig. 1. SVD-2 layout (described in the text).

3. the multicell threshold Cherenkov counter (TCC), with the $\pi/K/p$ thresholds of 3/11/20 GeV/c.

Data taking was performed in the 70 GeV/c proton beam of IHEP accelerator with an intensity of $\approx (5 \div 6) \cdot 10^5$ protons/cycle. The total statistics of $5 \cdot 10^7$ inelastic events was obtained. The sensivity of this experiment for inelastic pN-interactions, taking into account the trigger efficiency, was 2.3 nb^{-1}.

3 Sample I: K_s^0 decaying inside the vertex detector (decay region 0.2 - 35 mm).

After the first SVD-2 pentaquark publication[9] (January, 2004) new improved algorithms of the tracks reconstruction had been developed. It increased 3-4 times the available number of K_s^0 decays inside the vertex detector and essentialy improved the experimental K_s^0 mass resolution. The selected events were having a well defined secondary vertex in the region of $0.2 - 35$ mm along the beam direction from the beginning of the active target (corresponding to the sensitive area of the vertex detector). Secondary tracks were traced to the magnetic spectrometer to obtain their momenta. About $3{\cdot}10^4$ kaon candidates in the events with the number of primary charged tracks $N_{ch} < 8$ were selected, to reduce the combinatorial background in further analysis. Primary particles were traced to the spectrometer and two-body invariant mass distributions were built using previously selected neutral particles in association with primary vertex tracks. $K_s^0\pi^+$ and $\Lambda\pi^+$ invariant mass spectra showed that the masses and widths of K^{*+}(892)-meson and Σ^+(1385)-baryon are consistent with PDG tables[22].

The pK_s^0 invariant mass spectrum is shown in Fig.2. An excess of s=205 signal over b=1050 background events is observed in the area of interest, with the significance of s/$\sqrt{s+b} = 5.8$.

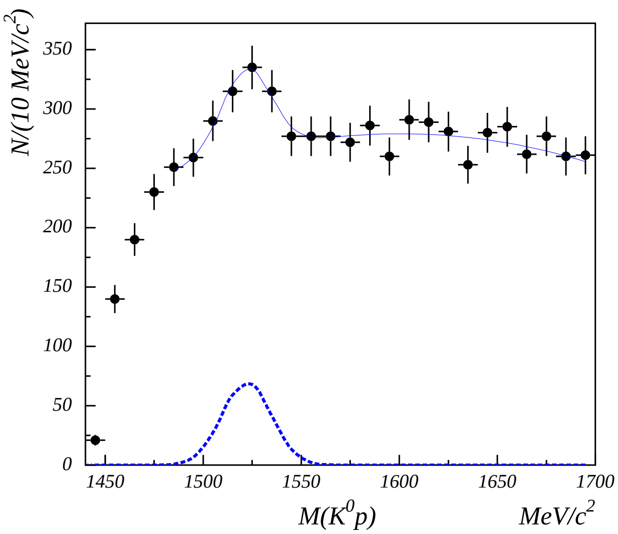

Fig. 2. Sample I: The (pK_s^0) invariant mass spectrum for the events with $N_{charged} < 8$. The dashed line stands for the peak extracted from the fit.

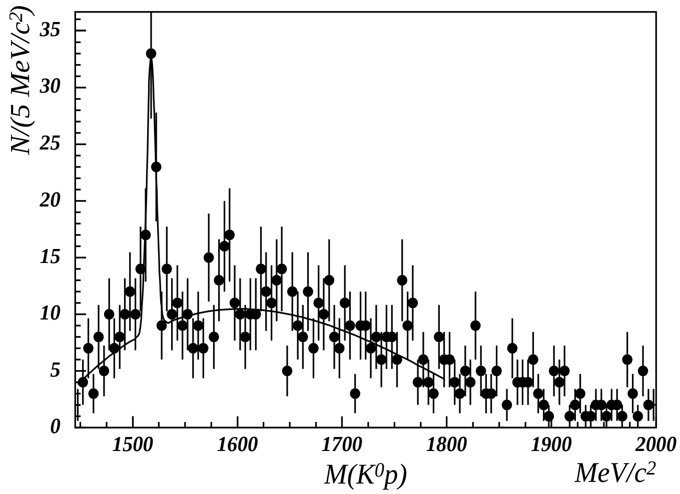

Fig. 3. Sample I: The (pK_s^0) invariant mass spectrum for K_s^0 decaying inside the vertex detector with additional quality cuts explained in text.

To estimate the natural width of the observed peak we selected events with the best reconstruction accuracy, applying the track quality cuts:

- $D < 2\sigma$,
  where D is the distance of the closest approach for V^0 tracks and σ is a calculated error,
- $N_{hits} \geq 12$,
  where N_{hits} is the number of hits for the track in the spectrometer planes.

With that, we obtained the mass resolutions 3.98 MeV/c^2 for K_s^0 and 1.46 MeV/c^2 for Λ particles.

The background was reduced further with the selection of events with 3 $GeV/c < P_{proton} < 10$ GeV/c and $N_{ch} > 3$; the latter cut may correspond to the greater inelasticity of the events with the Θ^+ creation [23]. The result is shown in Fig.3. Here the curve stands for the normalized mixed-event background built of kaon and proton taken from different events with the same kinematic requirements. The distribution was fitted by the sum of Gaussian function and second-order polynomial background. The Gaussian sigma of 4.1 ± 1.0 MeV/c^2 is consistent with our estimate of the highest possible experimental resolution of the SVD-2 setup. Taking into account the experimental SVD-2 resolution (calculated using well-known resonances) it was estimated that the intrinsic width of the (pK_s^0)-resonance is $\Gamma < 14$ MeV/c^2 at 95% C.L. No signal was observed in the combinations of K_s^0 with a tracks of negative charge.

4 Sample II: "Distant" K_s^0 decaying outside the vertex detector (decay region $35-600$ mm).

To create a Sample II, K_s^0-mesons and Λ-hyperons were reconstructed by the following procedure. The events with $n_{ch} \leq 8$ in the primary vertex were reconstructed using the algorithm described in [9] and the spectrometer hits belonging to the reconstructed tracks were removed. The remaining spectrometer hits were used to search for tracks originating from secondary vertices in the region before the first spectrometer plane (decay region $35-600$ mm). The initial track candidate had to have at least 3 hits in the Y-planes which could be approximated by a polynomial function originating from the area of interest. For these candidates the hits in the U and V planes of the spectrometer were searched for and global track parameters were defined using magnetic field map. Tracks of opposite signs were combined to test on having a common secondary vertex. Based on the intrinsic tracking resolution of the spectrometer the minimum distance between two tracks was required to be less than 1 mm in the horizontal and 5 mm in the vertical directions. The efficiency of this method was estimated as 50%, it's lower than that for the reconstruction based on vertex detector information.

The resulting invariant masses of $(\pi^+\pi^-)$ and $(p\pi^-)$ combinations are shown in Fig.4a and 4b. The standard deviations in the mass distributions are 6.1 MeV/c^2 and 2.4 MeV/c^2 for K_s^0 and Λ masses respectively. The obtained tracks collection was used as an opportunity to check for the production of well-known resonances. For $\phi^0(1020) \to K^+K^-$ and $\Lambda^*(1520) \to K^-p$ (Fig.5) a TCC particle identification was used. The total number of detected $\Lambda^*(1520) \to K^-p$ decays was about $2 \cdot 10^4$. Using PDG data, we estimated our experimental mass resolutions as $\sigma_{\Lambda^*(1520)} = 2.4 \pm 0.9$ MeV/c^2 and $\sigma_{\phi^0(1020)} = 1.6 \pm 0.2$ MeV/c^2.

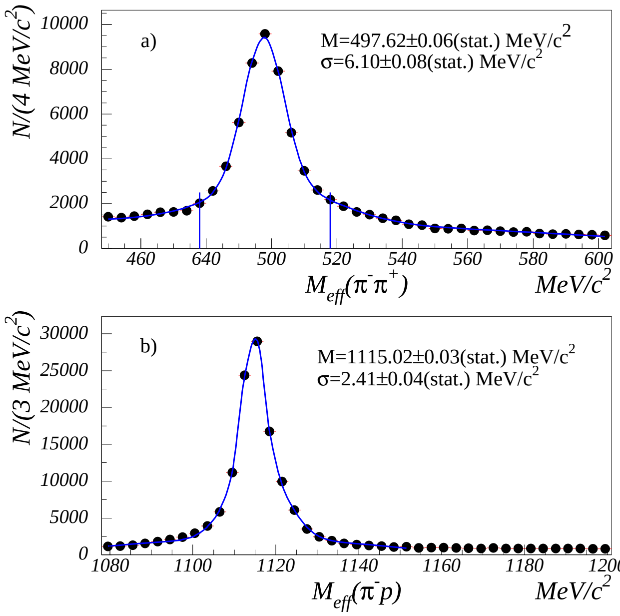

Fig. 4. Sample II: a). The $(\pi^+\pi^-)$ invariant mass spectrum. A window corresponding to $\pm 3\sigma$ is shown by the vertical lines. b) The $(p\pi^-)$ invariant mass spectrum.

The production of the resonances decaying into strange neutral particles was also studied. The $(\pi^+K_s^0)$ and $(\Lambda\pi^+)$ invariant mass spectra are shown in Fig.6. The clear peaks from $K^*(892)$ and $\Sigma^+(1385)$-resonances are seen. In total, the masses and widths of well-known resonances were all in a good consistency with their PDG values ([22]). For a $\Sigma^+(1385)$, when applying a $p_\Lambda < 6$ GeV/c cut, we observed a structure near 1480 MeV/c^2 (Fig.7). This peak may correspond to the $\Sigma(1480)$, marked as one star resonance in the PDG review([22]).

To search for the Θ^+-particle, the events with multiplicity of six or less charged tracks in the primary vertex were selected to minimize the combinatorial background.

About 52000 K_s^0-mesons in the mass window of ± 20 MeV/c^2 were found in the selected events. To eliminate contamination from Λ decays, candidates producing the effective mass of less than 1.12 GeV/c^2 for $(p\pi^-)$ mass hypothesis were rejected. The resulting invariant mass distribution is shown in Fig.4a.

Proton candidates were selected as positively charged tracks with a number of spectrometer hits more than 12 and momentum 8 $GeV/c \leq P_p \leq 15$ GeV/c. Pions of such energies should leave a hit in the Threshold Cherenkov Counter, so the absence of hits in TCC was also required. Moreover, for the events *with* a TCC hit of a positive particle taken as a proton, no significant peaks were found in the (pK_s^0) invariant mass spectra. We estimated that the π^+-background averages to no more than 10% under selection criteria used.

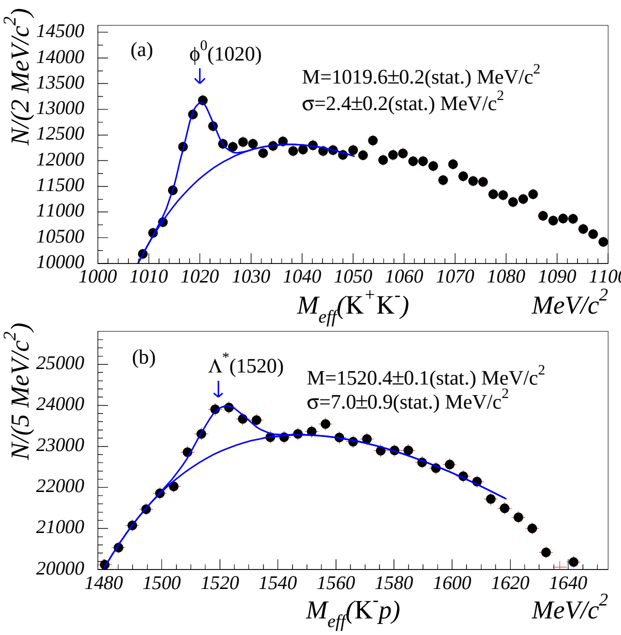

Fig. 5. Sample II: a) The (K^+K^-) invariant mass spectrum. b) The (K^-p) invariant mass spectrum.

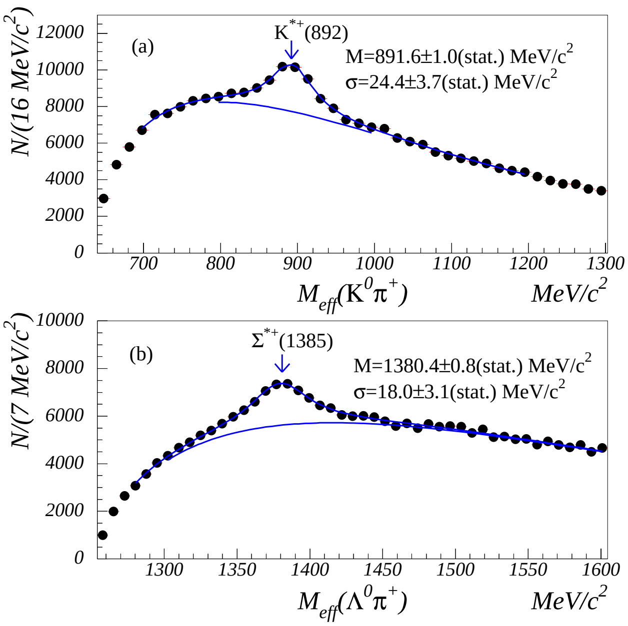

Fig. 6. Sample II: a) The $(\pi^+K^0_s)$ invariant mass spectrum. b) $(\Lambda\pi^+)$ invariant mass spectrum.

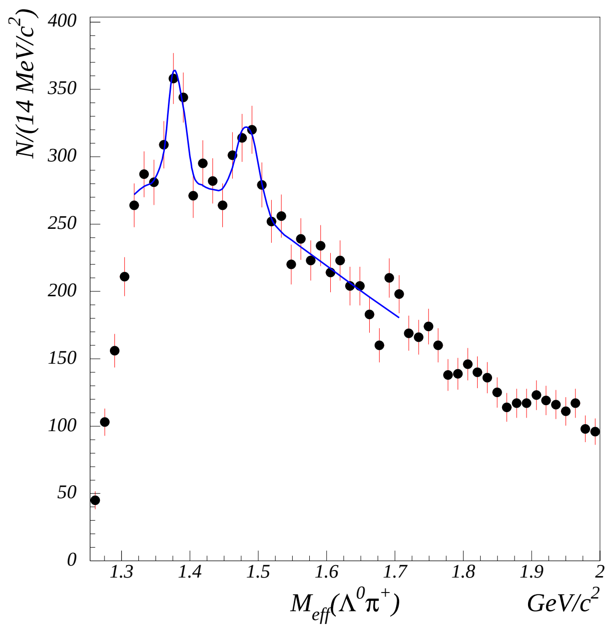

Fig. 7. The $(\Lambda\pi^+)$ invariant mass spectrum with the additional $p_\Lambda < 6\ GeV/c$ cut.

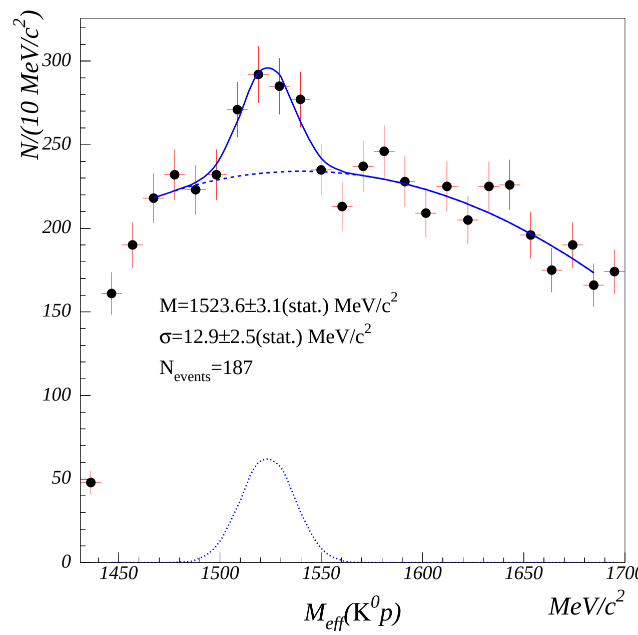

Fig. 8. Sample II: The (pK^0_s) invariant mass spectrum with the cuts explained in text.The dotted line in the bottom stands for the peak extracted from the fit.

Effective mass of the pK^0_s system is plotted in Fig.8. A peak is seen at the mass $M = 1523.6 \pm 3.1\ MeV/c^2$ with a $\sigma = 12.9 \pm 2.5\ MeV/c^2$. The distribution was fitted by a sum of a Gaussian function and second-order polynomial background. There are s=187 events in the peak over b=940 background events. The statistical significance for the peak is $s/\sqrt{s+b} = 5.6$

Two different models were tried to describe the background. The first was taken from RQMD Monte Carlo (Fig.9a) [24] and the second from the mixed event approach (Fig.9b). Both of them fitted plausibly the experimental data.

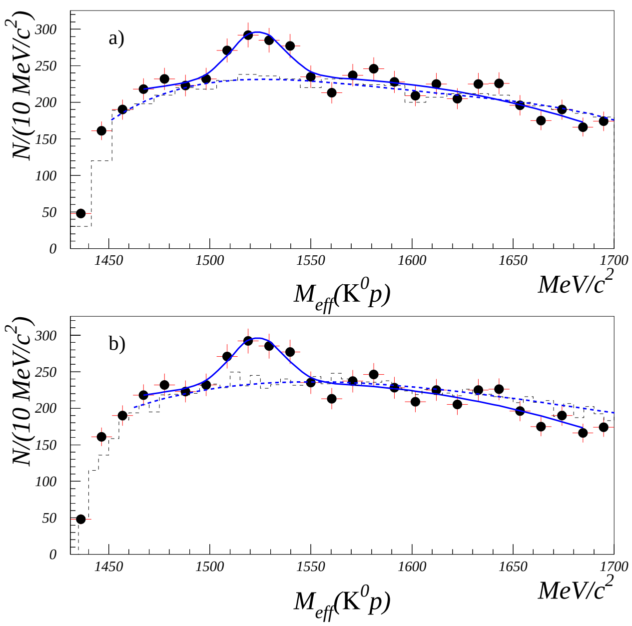

Fig. 9. Sample II: The (pK_s^0) invariant mass spectrum with different background descriptions represented by fitted dashed histogram: a) mixed-event model background; b) RQMD Monte Carlo background.

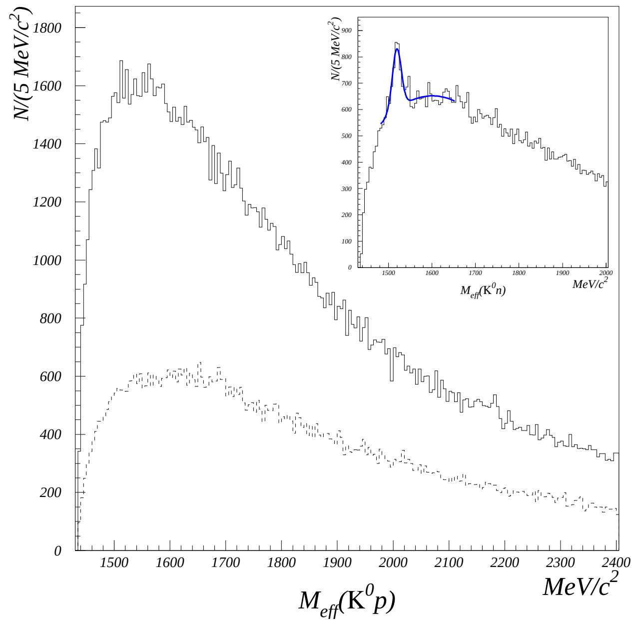

Fig. 10. The (pK_s^0) invariant mass spectrum for positively charged particles considered as a proton obtained from RQMD simulation. Dashed histogram represents the (pK_s^0) invariant mass spectrum with identified protons. Inset shows the (nK_s^0) invariant mass spectrum.

It was verified that observed pK_s^0-resonance can not be a reflection from other (for example $K^{*\pm}(892)$ or Δ^0) resonances. The mechanism of producing spurious peak around 1.54 MeV/c^2 involving K_s^0 and Λ decays overlap as suggested by some authors [26, 27] was also checked and no ghost tracks were found.

5 Monte-Carlo simulation of pA-interactions.

The invariant mass spectra of different particles and K_s^0 in pA collisions have been simulated by means of RQMD 2.3 event generator[24].

The RQMD generator produces spectra including short lived resonances. We used these spectra as input data for GEANT 3.21 package[25] to achieve a set of final state particles (K_s^0 and others) which are detected by apparatus. This set of particles was used to implement experimental cuts and to produce invariant mass spectra. The (nK_s^0) invariant mass spectrum clearly shows peak of $\Lambda^*(1520)$ with 30% enhancement over combinatorial background. In contrast, the mass spectrum of the pK_s^0 system is smooth and contains no fluctuations exceeding statistical errors on the background(Fig.10).

6 The x_F-distributions and cross sections.

We performed two searches for Θ^+ particle using SVD '2002 data. Their independence is based primarily on using V^0 candidate vertices in different regions. In both cases, numerous checks were made on possible peak imitations. For the kinematic reflections ($K^*(892)^+ \to \mathrm{K}^0 p$, $\Sigma(1385)^+ \to K^0 p$, etc.) and mechanisms with ghost tracks described in[26, 27] null results were obtained. A smooth shape of mixed-event background also excludes the possibility of generating the sharp peak due to the applied cuts and the detector acceptance. A narrow shape of the peak by itself makes it very difficult to be generated by any kind of reflections or kinematic constraints on the data.

It is impossible to determine the strangeness of this state in such an inclusive reaction, however we did not observe any narrow structure in $(\Lambda\pi^+)$ invariant mass spectrum in $1500 \div 1550$ MeV/c^2 mass region (Fig.6b), expected for a particle with the negative strangeness.

Our search for Θ^+-particle is an inclusive experiment with a significant background contribution. We have made an attempt to apply a subtraction method to investigate Θ creation region in terms of x_F. An effective mass distribution around the peak was fitted with a sum of background (B) and Gaussian functions, the latter having a mean of m_0 and a standard deviation of σ. Background was taken as a product of a threshold function and a second order polynomial $P2$, $B(m) = P2(m)(1 - e^{-x_2(m-x_1)})$, m standing for the effective mass. All the fit parameters were given reasonable seeds but no boundaries to prove a fit stability. The peak region was defined as $m_0 - 2\sigma < m < m_0 + 2\sigma$. A number of effective background events under the peak, $N(B_{peak})$, was evaluated by integrating background function over the peak region. x_F distributions were taken

separately for a peak and an out-of-peak regions("wings"); the latter ranged from 1.4 to 1.7 GeV/c^2 with a peak region cut out, and a result was scaled to a $N(B_{peak})$. Assuming that the background characteristics were uniform, we subtracted "wings" distribution from the peak one. These operations were performed separately over the data from both samples.

Acceptance corrections were evaluated using a GEANT Monte-Carlo[25] for the Θ^+ registration only. We took into account a presence of K^0 decay in the selected region, geometry acceptances, instrumental efficiencies and cuts used in the analyses. We did not consider any other tracks, accompanying the theta creation. Theta particles were generated with a flat distribution over the $-1 < x_F < 1$ region with a $< P_t >= 0.52 GeV/c$, estimated from a Sample I data and typical for the heavy particle creation. A vertex of the decay was generated randomly over the measured beam spot in X and Y, and Z was taken in the centers of the targets. Reconstruction procedure was applied to the simulated detector hits, taking into account detector efficiencies. The overall result is shown in fig. 11. The lower absolute value and a fall at $x_F \to 1$ for the Sample I are dominated by the limited region allowed for the K_s^0 decay, and the narrow shape for the Sample II reflects the proton momentum cut used.

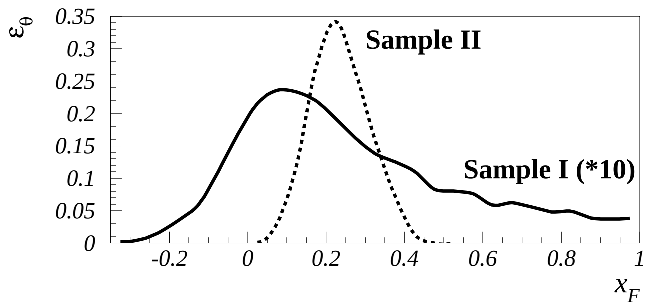

Fig. 11. Efficiencies of the Θ^+ registration in x_F. Data for different targets are weighted using the total numbers of K^0 events. The result for a Sample I is scaled by 10.

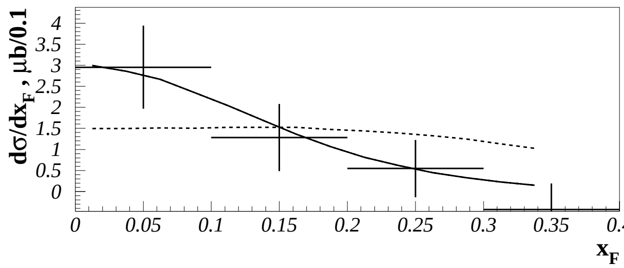

Fig. 12. x_F distribution for the Sample I. Crosses are experimental data, curves stand for a quark fragmentation(solid line) and a sum of quark and diquark fragmentation(dotted line) in a Regge-based model[28]. Y-axis: acceptance-corrected cross section over 0.1 in x_F. All the data are normalized to the 4.9 μb/nucleon for $0 < x_F < 0.3$ region

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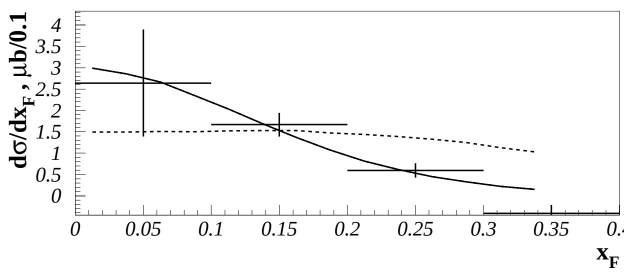

Fig. 13. The same as in fig.12 for the Sample II.

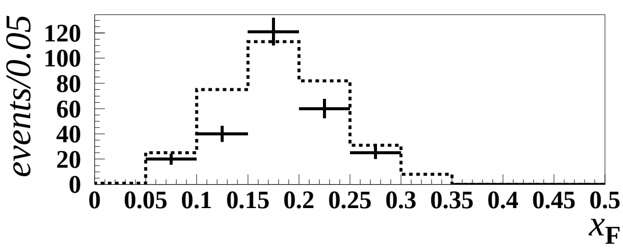

Fig. 14. A comparison of the Sample I (dotted histogram) to a Sample II (crosses) results.

The results are shown in figs.12 and 13. We plot also normalized curves of the predictions made in a Regge-based model[28]. In this model, an x_F distribution comes from the sum of quark fragmentation (bell-shaped around $x_F = 0$) and diquark one (seagull-shaped), each one with its proper weight. In [28] the weights were taken as 1:10, as coming from the analysis of non-exotic baryons creation. Our data may indicate a favoring to the quark fragmentation part of the model.

The Sample II has a specific narrow acceptance in x_F due to the proton momentum restrictions. We projected the x_F-result of Sample I to a Sample II to check the consistence of our observations. It was made by applying an *inverse* acceptance correction for Sample II to the result of Sample I. It is shown in fig.14 together with a raw (no acceptance correction) data for a Sample II. We found a plausible agreement of the distribution shapes and a certain difference in a total number of events. The latter makes a contribution to the cross section error calculations.

We have made an estimate of A-dependence in the Θ^+ creation. With SVD-2 vertex detector, Z-coordinate of primary vertex was reconstructed to a precision of about 70 μm, so the events belonging to different target planes were easily separated. For each material, a ratio was taken of the number of Θ^+ events to the number of all the K_s^0 events. Weighting it to a C^{12} value (table 1), we found no differences in the material dependence. Assuming that the observed K^0 events exhibit a $A^{0.71}$-dependence, we estimate that Θ^+ creation follows the same law (within errors).

The cross section of Θ^+ creation in pN interactions for $x_F > 0$ was evaluated from Sample I data (as having

Table 1. A-dependence. The fractions of Θ^+-events in the K^0 selection for different materials, weighted to a C^{12} result.

Target	Relative cross section
C^{12}	1.0 ± 0.22
Si^{28}	0.87 ± 0.29
Pb^{207}	1.09 ± 0.32

a better acceptance at $x_F \to 0$):

$$\sigma_{\Theta pN} \cdot Br(\Theta^+ \to pK^0) = \frac{\sigma_{pN} \cdot \epsilon_{corr}}{0.34} \frac{N_\Theta}{N_{pN} \cdot \epsilon_\Theta}$$
$$= 4.9 \pm 1.0(stat.) \pm 1.5(syst.)\ \mu b/nucleon,$$

where $\sigma_{pN} = 31.14\ \mu b$ is the inelastic proton-proton cross section[29], 0.34 is the PDG[22] value for the Br($K^0 \to \pi^+\pi^-$), N_Θ and N_{pN} are the numbers of events with a Θ^+ particle and all the events respectively and ϵ_Θ is the efficiency of Θ registration. A luminousity correction factor $\epsilon_{corr} = 0.84$ was evaluated from the following considerations. A trigger used for the physics events was developed initially as a Level I trigger, designed to be sensitive to all the inelastic pA-events in the target planes. A comparison to the "beam" trigger events showed that in our samples a registration of the primary vertices with a charged particles multiplicity $N_{ch} \leq 3$ is suppressed. We estimate the fraction of total inelastic events accepted by trigger as 0.63. Next, in a Sample I we cut out the events with $N_{ch} \geq 8$ accounting for 0.4 of all the registered events. Assuming that Θ^+-creation is 1) suppressed in the low N_{ch} region and 2) does not depend on the multiplicity in the high N_{ch} region, we derived a combined scaling coefficient for the Θ^+ cross section as $\epsilon_{corr} = 0.84$. As the better estimate of the cross section dependence on the multiplicity was not available, the resulting systematic error is rather large. With that correction, our integrated luminousity was $2.3 \cdot 10^{33} cm^{-2}$. It was implicitly assumed that σ_Θ in pA interactions also scales as $A^{0.71}$. This cross section value agrees within errors to the result published in [19], but differs from our earliest estimate[9]. The main reason is an unexpected form of x_F distribution, assumed flat in our first publications. Taking into account our situation of using inclusive data, and undiscovered yet mechanism of theta particle creation, we believe that the cross section value is subject to future investigations.

As positive as negative results of the theta particle searches were very often presented as the ratio of theta to $\Lambda(1520)$ cross sections. We estimate the latter value as $147 \pm 35\ \mu b/nucleon$, that agrees with the result obtained by EXCHARM collaboration[30] and gives the ratio of 0.07 assuming that the $\Theta^+ \to pK^0$ and $\Theta^+ \to nK^+$ decays have equal probabilities. However these two particles may have quite different creation mechanisms. For example, extracting x_F for $\Lambda(1520)$ by the same method as described above resulted in much more forward-oriented distribution (fig.15), than for a theta particle. It weakens the reasons of making this comparison. We may suppose that a best way to present such a ratio would be to accompany it with corresponding acceptances and x_F distributions.

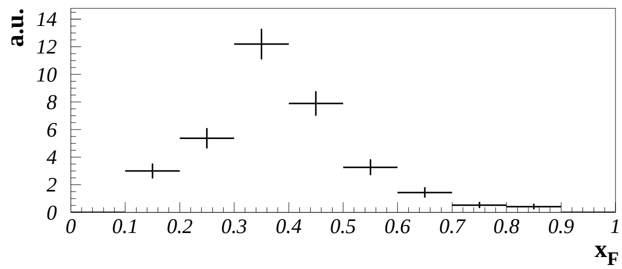

Fig. 15. An x_F distribution for a $\Lambda(1520)$.

7 Summary and Conclusions.

The inclusive reaction $pA \to pK^0_s + X$ was studied at IHEP accelerator with 70 GeV/c proton beam using SVD-2 detector. Two different samples of K^0_s, statistically independent and belonging to different phase space regions, were used in the analyses and a narrow baryon resonance with the mass $M = 1523 \pm 2(stat.) \pm 3(syst.)\ MeV/c^2$ was observed in both samples of the data. We observed the total of s=392 signal events over b=1990 of background. Using additional track quality cuts we obtained $\Gamma < 14\ MeV/c^2$ on 95% C.L. The statistical significance of the peak can be estimated to be (for different estimators):
s/$\sqrt{b} = 8.7$, s/$\sqrt{s+b} = 8.0$, s/$\sqrt{s+2b} = 5.9$.
The new analysis and larger statistics confirm our previous result[9]. The resonance observed is not a statistical fluctuation neither induced by background processes. We plan to continue our investigations of the creation mechanisms of pK^0_s resonance, momentum and angular dependencies and cross sections. The cross-section estimate for $x_F > 0$ ($\sigma \cdot BR(\Theta^+ \to pK^0) = 4.9\ \mu b$) was obtained. x_F distribution was found to peak at zero with $< |x_F| > \approx 0.1$, that agrees qualitatively to a Regge-based model[28]. While in agreement with evidences of Θ^+ observation, there is no direct contradiction to null results in hadron-hadron fixed target experiments (e.g. [31]), mainly due to different acceptances at $x_F \approx 0$.

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